Predictability and Coupled Dynamics of MJO During DYNAMO

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Award Number: N00014-13-1-0133

LONG-TERM GOALS

Our long-term goal is to develop both a coupled ocean-atmosphere model and a statistical forecasting model that have significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

OBJECTIVES

The objectives and immediate scientific goals of the proposed research are:

1. *Develop and test a WRF-ROMS regional coupled model (SCOAR2) for MJO predictability and feedback process studies on diurnal to intraseasonal time scales;*
2. *Develop a Linear Inverse Model (LIM) for MJO predictions and apply it in retrospective cross-validated forecast mode to the DYNAMO time period.*

APPROACH

We are working as a team to study MJO dynamics and predictability using several models as team members of the ONR DRI associated with the DYNAMO experiment. This is a fundamentally collaborative proposal that involves close collaboration with Dr. Arthur J. Miller of the Scripps Institution of Oceanography. The results presented here include collaborative work involving both Seo and Miller plus current SIO Ph.D. student Mr. Nick Cavanaugh, because we have discussed, instigated and synthesized each others' research activities and results by keeping in close contact via email and by meeting at various conferences during the past year.

The primary questions we are addressing are:

1) *Do the effects of mesoscale SST on the surface fluxes of heat and momentum introduce significant changes in the amplitude, structure, wavenumber and frequency of the MJO's?*

This can be addressed by running models in both coupled and uncoupled mode and comparing the structures of the MJO's produced. The focus here is on how oceanic mixed layer coupling with the atmospheric boundary layer transfers heat and energy to the overlying large-scale atmospheric MJO dynamics, and then on how changes to the mixed layer induced by diurnal cycle forcing and surface gravity wave processes alter these effects.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Predictability and Coupled Dynamics of MJO During DYNAMO**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceanographic Institution,Woods Hole,MA,02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2) *What are the consequences on the predictability of regional MJO development when mesoscale ocean-atmosphere coupling is allowed to influence the evolving MJO?*

Does the intrinsic variability (e.g., atmospheric storms) in the domain increase with these mesoscale feedbacks present, thereby lowering the predictability of MJO regional response? Or do the boundary conditions and large-scale dynamics of MJO strongly control the regional response? These uncertainty issues can be quantified by comparing sensitivities to initial conditions, boundary conditions, coupling time step, and physics parameterizations using models in coupled versus uncoupled mode and in high-resolution versus coarse-resolution mode, for both perfect model experiments and runs compared with observed events.

3) *How much predictive skill for MJO evolution can be obtained using a Linear Inverse Model as a statistical forecasting tool?*

Multiple studies have suggested that the MJO may provide an avenue for predictability beyond the traditional 2-week limit MJO hindcast skill studies utilizing high-dimensional numerical models have increased in recent years. Comparatively, there are relatively few statistical forecasts relevant to the MJO. The Linear Inverse Model (LIM, Penland and Magorian 1993) constitutes the least complex form of a reduced stochastic-dynamic climate model (Majda et al. 2009) and has been constructed for atmospheric diagnostics and prediction in several studies (e.g., Winkler et al. 2001, Newman et al. 2003) and coupled atmosphere-ocean modeling (Newman et al. 2009). The models in these studies have comparable predictive capacity to global circulation models for short-term predictions (intraseasonal and shorter), even though they have far fewer degrees of freedom.

WORK COMPLETED

Since the start of this current award in spring, 2013, we have contributed to the following subset of accomplishments of the multi-institutional team:

a. Run SCOAR2 (WRF-ROMS) in downscaling mode for the 2nd MJO event during the DYNAMO period (led by Seo, WHOI, with Miller, SIO)

b. Analyzed SCOAR2 for several years to determine how well MJO's are simulated (led by Seo, SIO, with Miller, SIO)

c. Testing sensitivity to ocean-atmosphere coupling time step (1hr to 1day) for SCOAR2 (led by Seo, WHOI, with Miller, SIO)

d. Developed Linear Inverse Model LIM of MJO predictability (led Cavanaugh and Miller, SIO, with Seo, WHOI)

e. Tested LIM skill in retrospective forecast model for DYNAMO time period (led by Cavanaugh and Miller, SIO, with Seo, WHOI)

f. Attended ONR PI meetings associated with the DYNAMO experiment (Seo, WHOI and Miller, SIO)

RESULTS

The following summarizes our most interesting and important results during the first year of collaborative research under this research project.

1. SCOAR2 MJO modeling

The second version of the Scripps Coupled Ocean-Atmosphere Regional Model (SCOAR2) has been developed and extensively tested for the DYNAMO period with particular emphasis on the role of the diurnal cycles in the upper ocean and the atmospheric convection. Better understanding of such will improve the extended-range (1 week to 1 month) forecasts of MJO events for practical use by the Navy. The results have important implications pertaining to questions on what atmospheric convection and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts.

SCOAR2 for DYNAMO is configured as the tropical channel model for improved depiction of circumglobal tropical atmospheric circulation. To better capture the thin (~3 meters) diurnal warm layer during DYNAMO, large number of vertical layers are allocated in the upper ocean to allow 4-5 layers in the upper 1-meter and 33 layers in the upper 55 meters. WRF and ROMS share the identical grids and horizontal resolution (40 km). A series of 5-member ensemble simulations has been carried out for the 30-day period from Nov. 14 – Dec. 13 2011 covering the suppressed and the active phase of the second MJO event (hereafter MJO2) during DYNAMO. Each ensemble run employs different coupling frequencies (CF) ranging from 1-hour (CF1), 3-hours (CF3), 6-hours (CF6), and up to 24 hours (CF24) to explicitly test the effect of resolving diurnal cycle in MJO simulation.

a. Simulated MJO2 rainfall and sensitivity to CF

Fig. 1 compares time-longitude evolutions of precipitation (10°S-10°N). The MJO2 event is identified as the intense precipitation episode at 80°E on November 24. The simulated precipitation from CF1, CF6 and CF24 shows reasonable skill in terms of the timing and propagation speed, considering that the peak rainfall occurred 10 days after the initialization. Interestingly, rainfall intensity is weaker with less frequent coupling. This is confirmed by the time-series in rainfall in Fig 1e showing the maximum rainfall of 1.3 $mmhr^{-1}$ in CF24 in comparison to 2 $mmhr^{-1}$ in CF1. Therefore, there appears to be a systematic response in precipitation amount associated with the MJO2 to the amplitude of diurnal cycle. The aim of the project is to carry out in-depth analyses to understand the cause of this relationship.

b. Upper ocean process during MJO2

The upper ocean prior to MJO2 is characterized by strong warming and enhanced diurnal cycle. Fig. 2 compares the evolution of temperature anomaly from CF1, CF6, and CF24 during Nov. 14-30 sampled along the R/V Revelle track. The upper ocean warming in all three cases peaks on Nov. 20-21 with the maxima at about 5 m depth, which precede the atmospheric convection on Nov 24. This is then followed by sudden cooling during the active phase of MJO. On top of this intraseasonal variation in SST, there is also a pronounced diurnal SST variability during the pre-convection period, with thickness of diurnal warm layer reaching up to 3 m in CF1 and CF6. The sudden collapse of the diurnal warm layer is seen during the active convection period after Nov. 24. CF1 exhibits the greatest amplitude in the diurnal cycle as well as the largest warming of the upper ocean during the pre-convection period, while CF24 lacks the diurnal cycle in SST and produces less warm upper ocean. This difference is further illustrated in Fig. 2b,d,f, which compare the mean profiles of temperature overlaid with its ±1 diurnal standard deviation in each case. The enhanced diurnal variability, confined in the upper 5 m of the ocean, is stronger in CF1 than CF6, whereas CF24 lacks the diurnal variation. While the mean SST appears to be slightly warmer in CF24 than

CF1, due to the large range of diurnal variation in temperature, higher SST is achieved on diurnal timescales in CF1 during the pre-convection period.

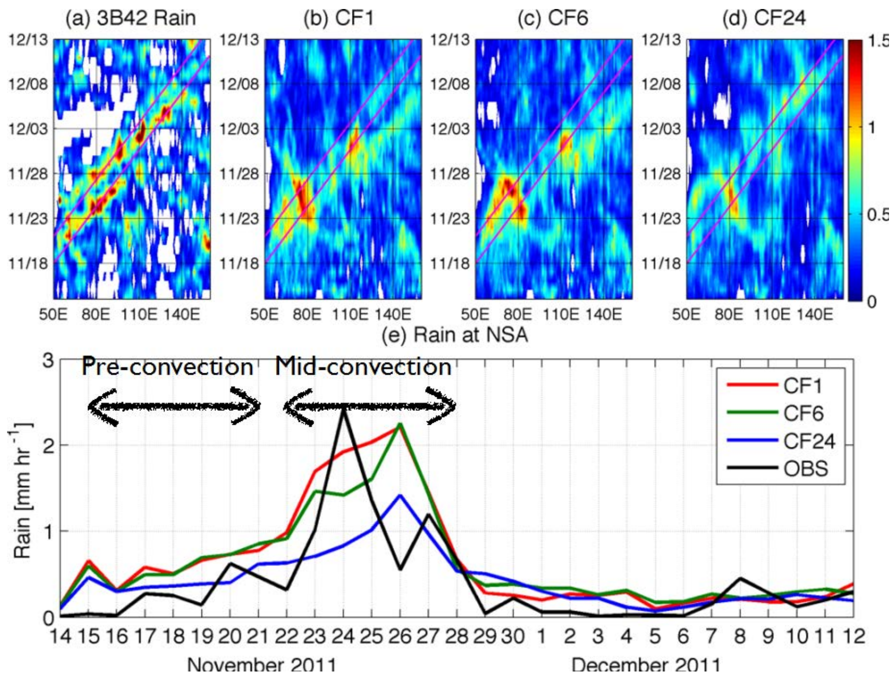

Figure 1. Time-longitude diagrams of precipitation rate [mm hr^{-1}] over 10°S-10°N from (a) TRMM 3B42, (b) SCOAR2 CF1, (c) CF6, and (d) CF24. (e) Daily precipitation over the northern DYNAMO array (73.15-80.5°E and 0.69°S to 6.91°N). The straight diagonal lines, identical in (a)-(d), denote the eastward propagating speed of 5 ms^{-1} beginning at the onset of rainfall event from (a).

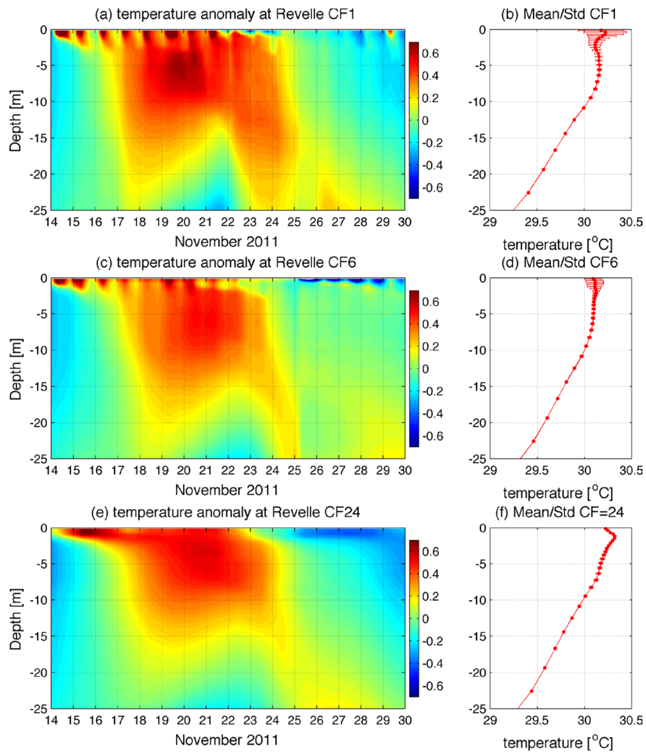

Figure 2. (Left) Time-depth diagrams of the upper ocean temperature [°C] sampled along the Revelle track from (a) CF1, (c) CF6 and (e) CF24. (Right) Mean temperature profiles overlaid with the diurnal standard deviation.

c. Impact on atmospheric convection

Fig. 3 a-c show the depth-time diagrams of the atmospheric specific humidity (q) anomalies over the northern DYNAMO region from the ERA-Interim and two model runs, CF1 and CR24. In both reanalysis and the model, pre-convection period is dominated by the drying of the atmosphere. A gradual moistening of the atmosphere is seen from Nov. 20, which then peaks on Nov. 24-26 during the active phase. The anomalous moistening appears to be stronger in CF1 than CF6 (not shown), and than CF24. Mean vertical distribution of specific humidity during the pre- (Fig. 3e) and mid-convection (Fig. 3f) periods suggests that the air column is moister with more frequent coupling.

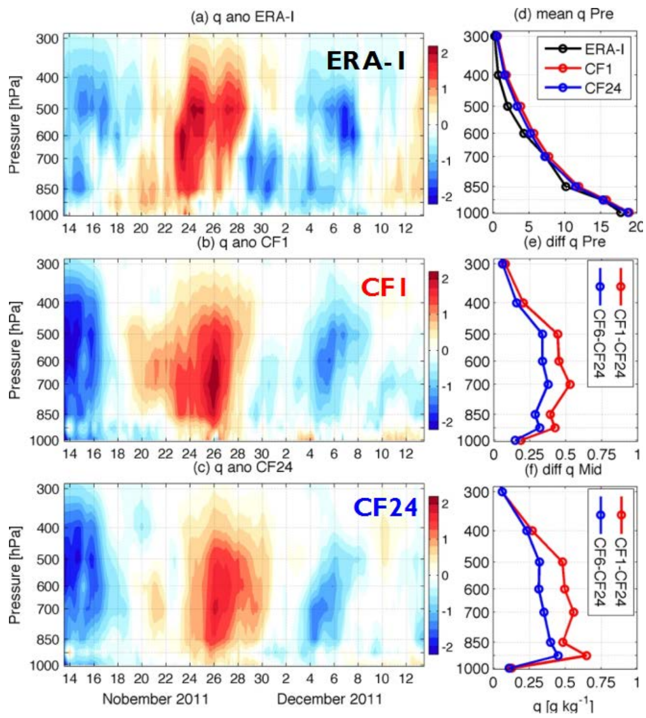

Figure 3. Time-height diagrams of the atmospheric specific humidity (q) anomaly [g kg^{-1}] over the northern DYNAMO array from (a) ERA-Interim Reanalysis, (b) CF1, and (c) CF24. (d) shows the mean q profiles during the pre-convection period, while (e) and (f) show the difference in q between (red) CF1-CF24 and (blue) CF6-CF24.

d. Moist Static Energy (MSE) budget analysis

The column-integrated MSE budget analysis has been carried out to elucidate process that relates the diurnal cycle to the convection intensity. Fig. 4a compares the individual MSE budget terms from different CF experiments during the pre-convection period.

$$\underbrace{\langle m_t \rangle}_{\textit{tendency}} = \underbrace{-\langle v_h \cdot \nabla m \rangle}_{\textit{horizontal advection}} \underbrace{-\langle \omega m_p \rangle}_{\textit{vertical advection}} + \underbrace{(LH + SH)}_{\textit{latent+sensible flux}} + \underbrace{\langle LW + SW \rangle}_{\textit{long+shortwave flux}}$$

The result clearly illustrates that more frequent coupling (and hence stronger diurnal cycle amplitude) leads to greater MSE import to the air column via turbulent heat flux (LH dominant). LH is the only significant source term that accounts for a more expedited rate of MSE recharge with higher coupling frequency. During the active phase of MJO (Fig. 4b), vertical advection discharges the MSE via deep convection and precipitation, which also appears to show some

correspondence to the coupling frequency. Turbulent and radiative heat fluxes continue to be the source terms of MSE during this phase.

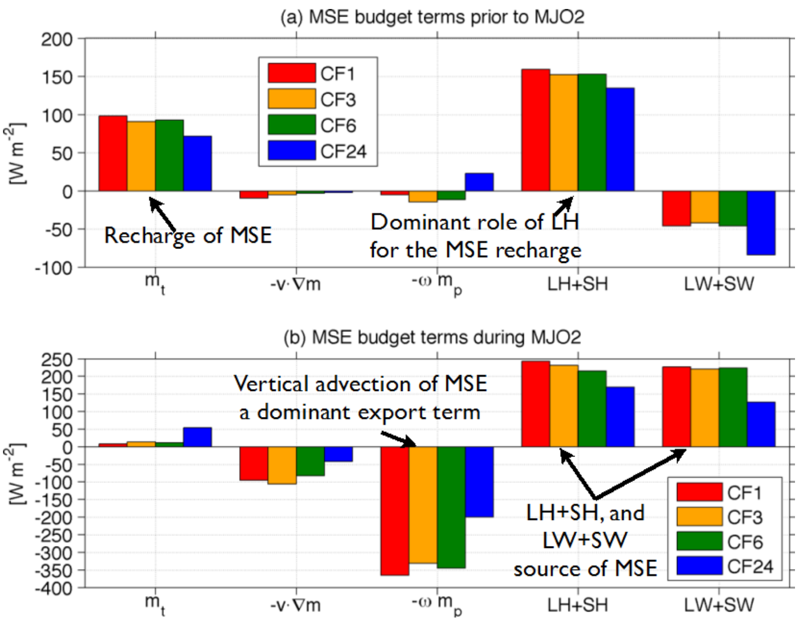

Figure 4. Column integrated MSE budget terms, color-coded to represent different coupling frequencies, for (a) prior to and (b) during the MJO2 event.

e. Summary

By using a set of SCOAR model experiments with varying CFs, we have begun to identify an important role that the diurnal cycle plays during the suppressed and the active phases of MJO2 during DYNAMO. The budget analysis suggests that during the suppressed phase, the warmer SST, achieved by stronger diurnal cycle, allows greater release of latent heat to the atmosphere. This, in turn, leads to a more rapid recharge of column-integrated MSE during the suppressed phase, which then triggers more intensified convection and precipitation during the active phase. This lead-lag relationship in SST-convection is summarized in Fig. 5 showing the scatter plot between the pre-convection SST and the mid-convection rainfall. In general, there is a linear relationship between SST and rainfall amount. As more frequent coupling results in higher SST and stronger precipitation during DYNAMO, our result demonstrates robust sensitivity of MJO to SST via diurnal cycle on a local scale.

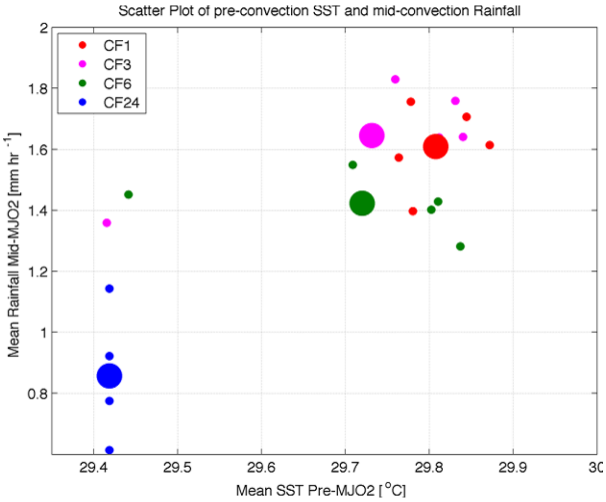

Figure 5. Scatter plots of pre-convection SST (defined as Nov. 15-19, 2011) and the precipitation rate [mm hr-1] during the mid-convection (defined as Nov. 20-26) averaged over the northern DYNAMO array. Small (large) circles represent the individual ensemble member (ensemble mean) values. Circles are color-coded to denote (red) CF1, (magenta) CF3, (green) CF6 and (blue) CF24.

2. Linear Inverse Model (LIM) of MJO predictability

In this part of the collaboration, we explore the use of atmospheric LIMs in the established context of MJO forecast verification to show that simple stochastic-dynamic representations of climate can provide competitive MJO hindcast skill. The results are discussed more completely by Cavanaugh et al. (2013).

a. Statistical method

Using the notation of Newman et al. (2009), the fundamental assumption underpinning LIM is that the governing dynamics of the system under consideration can be modeled as

$$\frac{d\mathbf{x}}{dt} = \mathbf{L}x + \xi \qquad (1)$$

where $\boldsymbol{x}$ represents an appropriate system state vector, $\mathbf{L}$ is a linear operator matrix, and ξ is a vector of stochastic temporally white but spatially structured Gaussian noise. For such a system, covariance matrices decay exponentially, so $\mathbf{L}$ can be estimated from observational estimates of covariance matrices $\mathbf{C}(\tau)$ where $\mathbf{C}_{ij}(\tau) = \langle \mathbf{x}_i(t+\tau)\mathbf{x}_j(t) \rangle$ evaluated at any 2 fixed lags. For some chosen lead-time τ_0, $\mathbf{L}$ is estimated as $\mathbf{L} = \tau_0^{-1}\ln\left[\mathbf{C}(\tau_0)\mathbf{C}^{-1}(\mathbf{0})\right]$. Eq(1) can then be solved for analytically: $\mathbf{x}(t+\tau) = \mathbf{G}(t)\mathbf{x}(t) + \varepsilon$ with $\mathbf{G}(\tau) = \exp(\mathbf{L}\tau)$ representing decaying, predictable signals at forecast lead time τ and ε is a random error vector with covariance $\mathbf{E}(\tau) = \mathbf{C}(0) - \mathbf{G}(\tau)\mathbf{C}(0)\mathbf{G}^{-1}(\tau)$. Error vector ε is Gaussian, growing as a function of τ regardless of initial condition at time *t*.

The LIM framework harnesses the covariability of climate signals to model the entire variance field, as opposed to statistical forecasts of only the real-time multi-variate MJO Index (RMM1 and RMM2) or other truncated or filtered MJO-only metrics. The data channels $\mathbf{x}$ may be time series of variables in physical space, or principal component (PC) time series of eigenmodes of the data in the desired forecast space. The diagonal components of $\mathbf{L}$ can be construed as climate viscosity or decay of each of the predicted variables independently, whereas the off-diagonal components of $\mathbf{L}$

represent modal interactions (if x is modal) or propagation (if x is spatial). Imaginary **L** components indicate principal oscillating patterns (POPs). Eigenanalysis of the covariance matrix of ξ produces the leading modes of stochastic forcing, which correspond physically to dominant modes of turbulent or chaotic energy parameterized by LIM as noise.

We use a reduced climate state $\mathbf{x} = [\boldsymbol{\psi}\ \mathbf{O}]^T$, where $\boldsymbol{\psi}$ is the PCs associated with the leading EOFs of 850mb and 200mb stream function anomalies from the NCEP RA-2 and **O** is the PCs of outgoing long-wave radiation anomalies from the NOAA OLR dataset. All variables are truncated to T21 resolution, mapped to 25°S – 25N, and smoothed with a 7-day filter. Unfiltered data withheld from the training set are projected onto the leading EOFs from the smoothed data to produce out-of-sample hindcasts. These smoothing techniques attenuate unpredictable (high-frequency) signals that corrupt LIM dynamics via aliasing, but MJO hindcast skills are insensitive to these filtering choices. Three-week tropical hindcasts were initiated for each day Jan 1, 2009 – Dec 31, 2012, for various combinations of EOFs. LIM hindcasts are cross validated by excluding data during the year the hindcast is constructed. Model hindcasts are projected on WH04 RMM indices for selected hindcast periods for hindcast skill verification.

b. Skill levels for MJO retrospective forecasts

Results (Cavanaugh et al., 2013, *Climate Dynamics, sub judice*), show that LIM skill is on the low end of current full-physics numerical models but within the model spread for both bivariate correlation (Fig. 6) and RMSE. This study highlights that extremely simple empirical models perform competitively in MJO hindcasts. It also provides a skill baseline for future implementations of reduced tropical stochastic climate models.

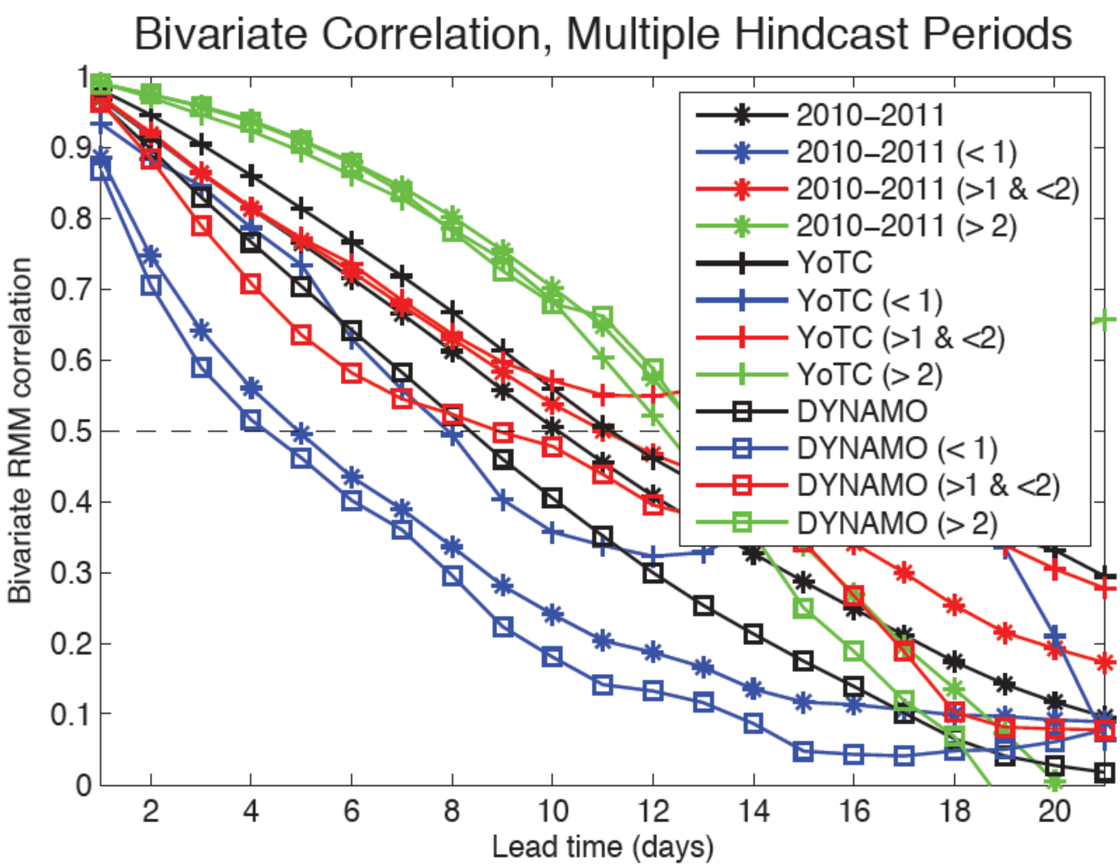

Figure 6. MJO skill (correlation) over multiple intervals and MJO amplitudes.

The LIM performs particularly well during mature stages of the MJO (Fig. 7). At these times, LIM skill is on par with numerical model skill over the entire period. This suggests either that the LIM formulations here are missing key components of MJO initiation and amplification that are not linearly related to **x** or that MJO amplification marks a period of dominantly non-linear deviation from an otherwise linear system that is better captured by numerical models. Alternately, smoothly propagating mature MJO events whose amplitudes and phase speeds are well captured by LIM suggests that at maturity, MJO propagation behaves as a dominantly linear system of traveling waves.

There are many possible extensions to the LIMs presented here: include seasonal cyclostationary time-dependence by conditioning **L** and ξ on the time of the year; include ocean coupling in the LIM; consider non-Gaussian statistics, and correlative and/or additive noise.

This statistical modeling work benefited from a serendipitous collaboration that developed with Prof Brian Mapes (Miami) and his Ph.D. student Mr. Teddy Allen (RSMAS) by our encountering them at one of the DYNAMO workshops. They were also involved in developing a LIM of MJO predictability. Instead of competing with them, we merged our efforts and have submitted a joint paper on this results (Cavanaugh et al., 2013).

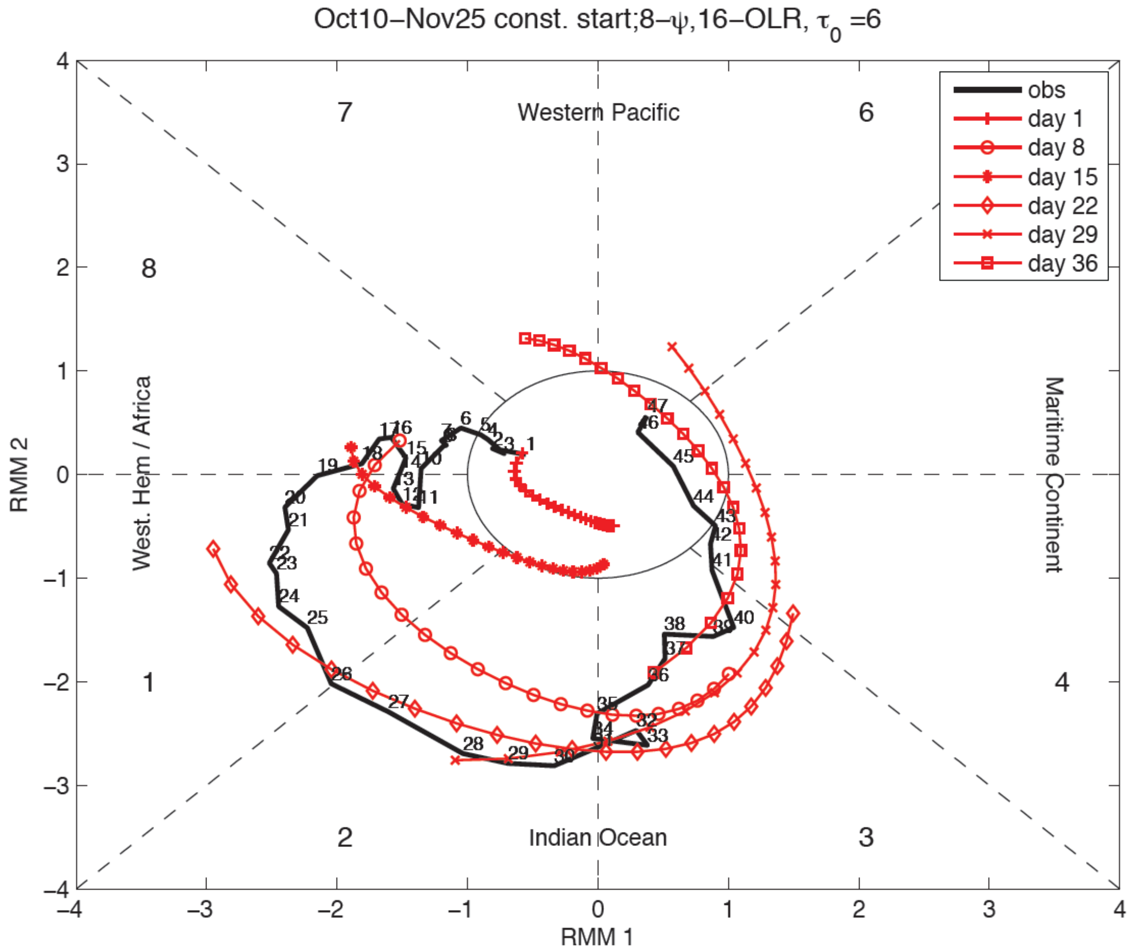

Figure 7. Multiple 3-week hindcasts for YoTC E MJO initialized at multiple days over the event.

IMPACT/APPLICATIONS

We continue to be in contact with other DRI MJO modelers (e.g., S. Chen, NRL; C. Zhang and M. Ulate, Miami, T. Jensen, Stennis. D. Waliser, JPL, R. Murtugude, UMd) for comparing simulations in the DYNAMO and YOTC frameworks.

We also continue to discuss our research results with Dr. Mark Swenson, Chief Scientist, FNMOC, to determine how effort might eventually be used to improve forecasting of MJO activity for practical use by the Navy. COAMPS, with specified SST, is currently available for practical regional forecasts. We expect our research to better reveal how ocean-atmosphere mesoscale coupling can influence extended-range (1 week to 1 month) forecasts of MJO variations, what atmospheric convective and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts. As COAMPS soon will also include interactive ocean capabilities with NCOM in real-time mode, our results will additionally provide a comparison to COAMPS skill levels and help point the way in dealing with various regional modeling limitations as well. Extended-range dynamical forecasts in regions influenced by MJO are based on a dynamical process that has potentially useful skill levels. These forecasts are expected to be better than climatology and can contribute to establishing a smart climatology for these regions during times of MJO excitation. This forecast information can then be used in practical Naval operations planning. Dr. Swenson has agreed to continue to discuss our research results in the context of practical usefulness throughout the course of this research.

RELATED PROJECTS

CCSM4 modeling activities

We continue to collaborate with Dr. Aneesh Subramanian (Scripps Ph.D. 2012, formerly advised by Miller) who is independently funded as a post-doc with Dr., Guang Zhang (SIO), to study MJO convection schemes in CAM4. Subramanian contributes expertise in diagnosing and interpreting MJO behavior in this project. We recently completed our joint study of MJO in CCSM4 (which has a better representation of MJO than CESM) by considering the sensitivities of MJO activity in an altered background state due to a global warming scenario compared to present conditions (Subramanian et al., 2013). The extreme global warming climate is defined as the Representative Concentration Pathways (RCP) 8.5 scenario, which reflects the socio-economic pathway that reaches a radiative forcing of 8.5 W/m2 by the year 2100. The RCP8.5 run exhibits increased variance in intraseasonal precipitation, larger-amplitude MJO events, stronger MJO rainfall in the central and eastern tropical Pacific, and a greater frequency of MJO occurrence for phases corresponding to enhanced rain fall in the Indian Ocean sector. These features are consistent with the concept of an increased magnitude for the hydrological cycle under greenhouse warming conditions. Conversely, the number of active MJO days decreases and fewer weak MJO events occur in the future climate state. These results motivate further study of these changes since tropical rainfall variability plays such an important role in the region's socio-economic well being.

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